

Final Project Report - ONR Grant N00014-91-J-1433

Characterization of 3D Fault-Generated Seafloor Topography

PIs: Jian Lin, Peter R. Shaw, and Deborah K. Smith
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Summary of Completed Project

The long-range goal of this study is to understand how tectonic faulting affects the nature, morphology, and composition of the oceanic crust. In particular we seek to determine the effects of seafloor spreading rate and ridge-axis segmentation on the 3D characteristics of seafloor faults and fault-generated topography. During this award period, we achieved three project objectives: 1) we developed new statistical methods of extracting fault geometric information from multi-beam bathymetric data; 2) we developed 2D and 3D fault models that determine the kernel relationship between fault-generated topography and subsurface fault variables; and 3) we quantitatively characterized the style of tectonic faulting in the ONR Atlantic natural laboratory using the newly developed analytical techniques. These results are summarized below and are detailed in the publications listed.

1) Extraction of 3D Fault Information from Multi-Beam Data

We developed a new method of identifying faults from multi-beam bathymetric data using a curvature, rather than slope, analysis technique [Shaw, *Nature*, 1992; Shaw and Lin, *JGR*, 1993]. In this analysis, the seafloor bathymetry is first segmented into small circular patches; the curvature of each patch is then approximated by a best-fitting quadratic surface in a linear least-square sense. When combined with a running-window technique, this curvature method can effectively distinguish fault scarps from slopes of constructional volcanic features.

We applied the curvature and slope methods successfully to the Sea Beam data collected along the Mid-Atlantic Ridge axis between 23°-31°, producing fault maps for the entire area [Shaw and Lin, *JGR*, 1993]. The results show that faults are more linear and more closely spaced at mid-portion of a spreading segment. Towards segment offsets, however, the faults become oblique and the fault spacing increases. This along-axis variability testifies the strong control of ridge segmentation and crustal thickness on styles of faulting [Sempere, Lin et al., *MGR*, 1993; Lin and Bergman, *JGR*, submitted].

In addition to the along-axis variability, there exists additional across-axis asymmetry near segment boundaries. Crust at "inside" corners are more elevated than "outside" corners; residual gravity anomalies also indicate that the inside-corner crust is consistently thinner than the outside-corner crust [Escartin and Lin, *JGR*, 1995]. Such across-axis asymmetry and its off-axis variability may be explained by long-lived detachment faulting and cyclic magmatic/amagmatic extension at slow-spreading ridges [Tucholke and Lin, *JGR*, 1994; Lin et al., *Nature*, in prep.].

2) Determination of Relationship between Topography and Subsurface Fault Variables

Through boundary-element numerical modeling, we determined the precise kernel functions between surface expressions of faults, e.g., topography and gravity, and subsurface fault variables, such as fault depth, dip-angle, and lithosphere thickness. The developed models consider both 2D [Escartin and Lin, *JGR*, 1995] and 3D [Katzman, ten Brink, and Lin, *JGR*,

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1995; Shaw and Lin, *JGR*, submitted; Lin and Chen, *GRL*, submitted; ten Brink, Katzman, and Lin, *JGR*, submitted] fault geometries. We applied the kernel techniques in studying the Sea Beam bathymetry of the Mid-Atlantic Ridge and are successful in predicting the main characteristics of ridge-crest morphology and residual gravity. We also studied the effects of variable lithosphere viscosity on long-term survival of seafloor topography [Freed, Lin et al., *Geology*, in press].

Numerical modeling has yielded two important results: 1) Style of faulting is a strong function of local crustal thickness and spreading rate. Small, closely-spaced faults are predicted at fast-spreading ridges, hotspot-influenced ridges, and mid-points of long slow-spreading segments of thick crust. In contrast, large, widely spaced faults are predicted for slow-spreading segments of thin crust [Shaw and Lin, *JGR*, submitted]; 2) The gravity anomaly of individual normal faults at the Mid-Atlantic Ridge is predicted to be less than ~20 mgal for reasonable subsurface fault variables. Therefore although faulting is sufficient to produce the observed *across-axis* asymmetry in crustal elevation and gravity near ridge-axis offsets, it alone is insufficient to explain the *along-axis* "bull eyes" gravity anomalies that are as much as ~50 mgal along some segments of the Mid-Atlantic Ridge [e.g., Lin et al., *Nature*, 1990; Lin and Phipps Morgan, *GRL*, 1992].

3) Quantification of Tectonic Faults in the ONR Atlantic Natural Laboratory

We analyzed multi-beam bathymetry, HMR1 side-scan sonar, gravity, and magnetic data that we collected in the ONR Atlantic natural laboratory at 25.5°-27°N. The ONR Acoustic Reverberation corridor encompasses off-axis traces of nine spreading segments in 0-28 Ma crust, all bounded by non-transform offsets. We identified several new tectonic features in the region, including 1) Strong contrasts in seafloor elevation, faulting style, and crustal thickness between off-axis continuations of inside- vs. outside-corner crust; 2) Close-contoured, "boudin-shaped" gravity lows along off-axis continuations of segment centers, suggesting long-term (3-9 m.y.) magmatic pulses in the Mid-Atlantic Ridge [Lin, et al., *EOS*, 1993, 1995; *Nature*, in prep.]; 3) Strong correlations between abyssal hill morphology, e.g., RMS highs, and gravity-derived crustal thickness [Goff et al., *JGR*, in press]; and 4) Fast-propagating rifts in a slow-spreading environment [Tucholke, et al., *EOS*, 1995; *MGR*, in prep.].

Publications Supported by this Award

1) Papers Published in Refereed Journals (11 Total)

- Escartin, J., and J. Lin, Ridge offsets, normal faulting, and gravity anomalies of slow-spreading ridges, *Journal of Geophysical Research*, 100, 6163-6177, 1995.
- Escartin, J., and J. Lin, The Mid-Atlantic Ridge between 24° and 30°N, *Acta Geologica Hispanica*, 27, 33-49, 1992.
- Katzman, R., U.S. ten Brink, and J. Lin, Three-dimensional modeling of pull-apart basins: Implications for the tectonics of the Dead Sea basin, *Journal of Geophysical Research*, 100, 6295-6312, 1995.
- Ito, G., and J. Lin, Mantle temperature anomalies along the present and paleo-axes of the Galapagos spreading center as inferred from gravity analyses, *Journal of Geophysical Research*, 100, 3733-3745, 1995.
- Lin, J., and J. Phipps Morgan, The spreading rate dependence of three-dimensional mid-ocean ridge gravity structure, *Geophysical Research Letters*, 19, 13-16, 1992.
- Sempere, J.-C., J. Lin, H.S. Brown, H. Schouten, and G.M. Purdy, Segmentation and morphotectonic variations along a slow-spreading center: The Mid-Atlantic Ridge 24°-30°40'N, *Marine Geophysical Research*, 15, 153-200, 1993.

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- Shaw, P.R., Ridge segmentation, faulting, and crustal thickness in the Atlantic, *Nature*, 358, 490-493, 1992.
- Shaw, P.R., and J. Lin, Causes and consequence of variations in faulting style at the Mid-Atlantic Ridge, *Journal of Geophysical Research*, 98, 21,839-21,851, 1993.
- Smith, D.K., and J.R. Cann, Building the crust at the Mid-Atlantic Ridge, *Nature*, 365, 707-715, 1993.
- Tucholke, B.E., and J. Lin, A geological model for the structure of ridge segments in slow-spreading ocean crust, *Journal of Geophysical Research*, 99, 11,937-11,958, 1994.
- Zervas, C., J.-C. Sempere, and J. Lin, Morphology and crustal structure of the Atlantis transform, the Mid-Atlantic Ridge, *Marine Geophysical Research*, 17, 275-300, 1995.

2) Papers In Press or Submitted to Refereed Journals (7 Total)

- Freed, A.M., J. Lin, P.R. Shaw, and H. J. Melosh, Long-term survival of the axial valley morphology at abandoned slow-spreading centers, *Geology*, in press, 1995.
- Goff, J.A., B.E. Tucholke, J. Lin, G.E. Jaroslow and M.C. Kleinrock, Quantitative analysis of abyssal hills in the Atlantic ocean: A correlation between crustal thickness and extensional faulting, *Journal of Geophysical Research*, in press, 1995.
- Lin, J., and J. Y. Chen, Subsurface and surface loadings on the young oceanic lithosphere at the northern Mid-Atlantic Ridge, *Geophysical Research Letters*, submitted.
- Lin, J., and E.A. Bergman, Rift grabens, seismicity, and volcanic segmentation of a slow-spreading ridge: the Mid-Atlantic Ridge between the Kane and Atlantis transform faults, *Journal of Geophysical Research*, submitted.
- Shaw, W.T., and J. Lin, Models of oceanic ridge lithospheric deformation: Dependence on crustal thickness, spreading rate, and segmentation, *Journal of Geophysical Research*, submitted.
- Smith, D.K., J.R. Cann, M.E. Dougherty, J. Lin, S. Spencer, C. Macleod, J. Keeton, E. McAllister, R. Pascoe, B. Brooks, and S. Wanda, Mid-Atlantic Ridge volcanism from deep-towed side-scan sonar images, 25°-29°N, *Journal of Volcanology and Geothermal Research*, in press, 1995.
- ten Brink, U., R. Katzman, and J. Lin, Three-dimensional models of deformation near strike-slip faults, *Journal of Geophysical Research*, submitted.

3) Invited Papers in Non-Refereed Journals (5 Total)

- Fujimoto, H., W.B. Bryan, K. Kobayashi, H. Kinoshita, M. Tivey, P. Kelemen, A. Takeuchi, T. Matsumoto, H. Ishizuka, T. Furata, T. Fujiwara, J. Lin, H. Hotta, and G.M. Purdy, Diving and surface surveys of the western part of the Kane transform fault, *InterRidge News*, 3, 20&27, 1994.
- Kleinrock, M.C., B.E. Tucholke, and J. Lin, Ridge segmentation, migrating offsets, and crustal structure on the western flank of the Mid-Atlantic Ridge from 25°25'N to 27°10'N out to 30 ma, *Ridge Events*, 3, 5-7, 1992.
- Lin, J., A new look at the Mid-Atlantic Ridge, *Ridge Events*, 1, 1, 8, 1991.
- Lin, J., The segmented Mid-Atlantic Ridge, *Oceanus*, 34, 9-16, 1992.
- Lin, J., J. Karson, and J. Sinton, Experimental approaches to ridge segment structure and dynamics, *Ridge Events*, 5, 19-20, 1994.

4) Workshop Reports (3 Total)

- Lin, J., R. Searle, and J. Sinton, Segmentation and fluxes at mid-ocean ridges, In: *Reports of the InterRidge Meso-Scale Symposium and Workshops*, edited by H. Sloan, pp. 4-40, the InterRidge Office, Durham, UK, 1994.
- Lin, J., J. Karson, and J. Sinton, Design workshop for experimental approaches to ridge segment structure and dynamics (RISES), *RIDGE Workshop Rep.*, Woods Hole, Massachusetts, 24 p., 1995.

Parson, L.M., J. Lin, and C. Mevel, 4-D architecture of the oceanic lithosphere, *InterRidge Meso-Scale Workshop Report*, Durham, UK, 15 p., 1995.

5) Invited Presentations at Conferences (10 Total)

- Kleinrock, M.C., B.E. Tucholke, and J. Lin, The trace of non-transform offsets and the evolution of Mid-Atlantic Ridge spreading segments between 25°25' and 27°10'N over the past 30 m.y., *EOS Trans. AGU*, 73, 538, 1992.
- Lin, J., and J.Y. Chen, Lithospheric deformation near spreading segments along the Mid-Atlantic Ridge 24°-31°N: Observation and models, *EOS Trans. AGU*, 72, 260, 1991.
- Lin, J., D.K. Smith, and P.R. Shaw, Dynamic topography created by tectonic faults at the Mid-Atlantic Ridge, *EOS Trans. AGU*, 72, 466, 1991.
- Lin, J., J.R. Cann, Smith, D.K., M. Dougherty, S. Spencer, C. Macleod, J. Keeton, E. McAllister, R. Pascoe, B. Brooks, and S. Garland, Magmatic segmentation and axial rift structure along the Mid-Atlantic Ridge, *EOS Trans. AGU*, 73, 285, 1992.
- Lin, J., B.E. Tucholke, M.C. Kleinrock, and J.A. Goff, Variations in crustal faulting and magmatic accretion along the Mid-Atlantic Ridge and off-axis: Results from the western flank of the MAR at 25°25'-27°10'N, *EOS Trans. AGU*, 73, 538, 1992.
- Lin, J., B.E. Tucholke, and M.C. Kleinrock, Evidence from gravity and morphology for long-term variability in magmatic vs. tectonic extension at the Mid-Atlantic Ridge, *EOS Trans. AGU*, 74, 303, 1993.
- Smith, D.K., J.R. Cann, M.E. Dougherty, J. Lin, B. Brooks, S. Spencer, C.J. MacLeod, E. McAllister, R.A. Pascoe, and J.A. Keeton, Volcanism and faulting on the inner valley floor of the Mid-Atlantic Ridge (24-30°N), *EOS Trans. AGU*, 73, 568, 1992.
- Tucholke, B. E., and J. Lin, Detachment faulting and its relation to geologic structure at first- and second-order offsets of slow-spreading ridges, *EOS Trans. AGU*, 73, 286, 1992.
- Tucholke, B.E., J. Lin, and M.C. Kleinrock, Crustal structure of spreading segments on the western flank of the Mid-Atlantic Ridge at 25°25'-27°10'N, *EOS Trans. AGU*, 73, 537, 1992.
- Tucholke, B.E., M.C. Kleinrock, M. Tivey, and J. Lin, Fast-propagating rifts in slow-spreading crust, *EOS Trans. AGU*, 76, submitted, 1995.

6) Contributed Presentations at Conferences (25 Total)

- Brooks, B., D. K. Smith, J.R. Cann, M.E. Dougherty, J. Lin, S. Spencer, C.J. Macleod, E. McAllister, R.A. Pascoe, and J.A. Keeton, TOBI deep-towed side scan mosaics of spreading segments at the MAR (24°-30°N), *EOS Trans. AGU*, 73, 568, 1992.
- Cann, J., D.K. Smith, M.E. Dougherty, J. Lin, B. Brooks, S. Spencer, C.J. MacLeod, E. McAllister, R.A. Pascoe, and J.A. Keeton, Major landslides in the MAR median valley, 25°-30°N: Their role in crustal construction and plutonic exposure, *EOS Trans. AGU*, 73, 569, 1992.
- Chen, J.Y., and J. Lin, The isostatic and dynamic topography of the Mid-Atlantic Ridge 27-31°N, *EOS Trans. AGU*, 72, 466, 1991.
- Dougherty, M., J.R. Cann, Smith, D.K., J. Lin, S. Spencer, C. Macleod, J. Keeton, E. McAllister, R. Pascoe, B. Brooks, and S. Garland, Off-axis evolution of MAR axial valley morphology, *EOS Trans. AGU*, 73, 275, 1992.
- Escartin, J., and J. Lin, Gravity constraints on the style of crustal thinning at the Mid-Atlantic Ridge, *EOS Trans. AGU*, 74, 664, 1993.
- Freed, A.M., P.R. Shaw, J. Lin, and H.J. Melosh, Dynamic evolution of the oceanic lithosphere from an active to extinct spreading center, *EOS Trans. AGU*, 74, 600, 1993.
- Goff, J.A., M.C. Kleinrock, J. Lin, and B.E. Tucholke, Quantitative analysis of abyssal hill morphology within three segments: the west flank of the MAR 25°25'-27°10'N and 0-30 Ma, *EOS Trans. AGU*, 73, 538, 1992.

- Ito, G., and J. Lin, Geophysical constraints on the flow pattern and temperature anomaly of the Galapagos hotspot beneath the Galapagos spreading center, *EOS Trans. AGU*, 73, 583, 1992.
- Katzman, R., U.S. ten Brink, and J. Lin, 3-D modeling of pull-apart basins: Implications for the tectonics of the Dead Sea basin, *EOS Trans. AGU*, 75, 600, 1994.
- Kleinrock, M.C., B.E. Tucholke, and J. Lin, HAWAII MR1 sidescan sonar survey of the Mid-Atlantic Ridge rift valley from 25°25'N to 27°N, *EOS Trans. AGU*, 73, 567, 1992.
- Lee, S.M., J. Lin, and S.C. Solomon, A mechanism for near-ridge normal faulting at fast-spreading mid-ocean ridges, *EOS Trans. AGU*, 74, 297, 1993.
- Lin, J., and S.M. Lee, The causes of large 'half-graben' structures at the Mid-Atlantic Ridge and the implications for the lithosphere rheology, *EOS Trans. AGU*, 72, 261, 1991.
- Lin, J., B.E. Tucholke, and M.C. Kleinrock, Off-axis "boudin-shaped" gravity lows on the western flank of the Mid-Atlantic Ridge at 25°25'-27°10'N: Evidence for long-term pulses in magmatic accretion in spreading segments, *EOS Trans. AGU*, 74, 380, 1993.
- Lin, J., and W.J. Shaw, The spreading-rate dependence of mid-ocean ridge fault structure and its relationship to crustal thickness variations, *EOS Trans. AGU*, 75, 658, 1994.
- Lin, J., B.E. Tucholke, M.C. Kleinrock, and J. Escartin, Contrasting inside- vs. outside-corner crustal structure on flanks of a slow-spreading ridge, *EOS Trans. AGU*, 76, submitted, 1995.
- Shaw, P.R., and J. Lin, Causes and consequences of variations in faulting style at the Mid-Atlantic Ridge, *EOS Trans. AGU*, 73, 551, 1992.
- Shaw, P.R., B.E. Tucholke, and J. Lin, Large-scale tectonic fabric of the northern Mid-Atlantic Ridge flank, *EOS Trans. AGU*, 74, 306, 1993.
- Shaw, P.R., M.A. Tivey, B.E. Tucholke, M.C. Kleinrock, and J. Lin, Past plate motion recorded in abyssal hill lineations and magnetic lineations on the western flank of the MAR, 26°N, *EOS, Trans. AGU*, 75, 330, 1994.
- Shaw, W. J., and J. Lin, Three-dimensional modelling of thermo-mechanical structure of oceanic spreading centers: Effects of along-axis thickness variations associated with segmentation and hot spots, *EOS, Trans. AGU*, 75, 331, 1994.
- Smith, D.K., J.R. Cann, J. Lin, M. Dougherty, S. Spencer, C. Macleod, J. Keeton, E. McAllister, R. Pascoe, B. Brooks, and S. Garland, TOBI deep-tow side-scan survey of small volcanoes on the inner valley floor of the MAR (24°-30°N), *EOS Trans. AGU*, 73, 285, 1992.
- Spencer, S., J. Lin, D.K. Smith, J.R. Cann, E. McAllister, R. Pascoe, M. E. Dougherty, S. Garland, C.J. MacLeod, and J.A. Keeton, Nature of non-transform offsets on the Mid-Atlantic Ridge between 24 and 30°N, *EOS Trans. AGU*, 73, 553, 1992.
- ten Brink, U.S., R. Katzman, and J. Lin, Three-dimensional models of crustal deformation associated with strike-slip faults, *EOS Trans. AGU*, 75, 600, 1994.
- Tucholke, B.E., J. Lin, and T.B. Reed IV, Patterns of seafloor morphology observed along- and across-axis on the Mid-Atlantic Ridge, 24-27°N, *EOS Trans. AGU*, 72, 260, 1991.
- Tucholke, B.E. and J. Lin, Asymmetric crustal structure at ridge-axis offsets, Mid-Atlantic Ridge, *EOS Trans. AGU*, 72, 466, 1991.
- Tucholke, B.E., M.C. Kleinrock, W.K. Stewart, J. Lin, J. Goff, G. Jaroslow, B. Brooks, P. Lemmond, J. Howland, M. Marra, T. Reed, M. Edwards, J. R. Fricke, and U. Herzfeld, Geological and geophysical survey of the Mid-Atlantic Ridge flank at 25°25' to 27°10'N, *EOS Trans. AGU*, 73, 552, 1992.

7) Graduate Students Supported Under This Award (4 Total)

Javier Escartin, MIT-WHOI Joint Program in Oceanography

Garrett Ito, MIT-WHOI Joint Program in Oceanography

William Shaw, MIT-WHOI Joint Program in Oceanography

Andrew Freed, WHOI Guest Student and Graduate Student at University of Arizona